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# Effect of temperature on the exchange bias in FeMn/X/$Fe_{20}Ni_{80}$ (X = Ta, Gd) films

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# Effect of temperature on the exchange bias in FeMn/X/$Fe_{20}Ni_{80}$ (X = Ta, Gd) films

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**Abstract**. The influence of temperature on the exchange bias in the $Fe_{50}Mn_{50}$/X/$Fe_{20}Ni_{80}$ (X = Ta, Gd) films was investigated. It is shown that in the film structures without a spacer between FeMn and permalloy layers, the temperature dependence of the value of the exchange bias field is non-monotonous. The introduction of an ultrathin spacer leads not only to a change in the magnitude of the interlayer exchange coupling, but also to a change in the behavior of its temperature dependence.

## 1. Introduction

The effect of magnetic bias is required to develop the majority of the functional magnetic media in film modification, since it allows to minimize the magnetic uncertainty of the multi-domain state [1, 2]. Most often it is realized in the film structures containing exchange-coupled ferromagnetic and antiferromagnetic layers and, in this connection, is called exchange bias. The classical permalloy ($Fe_{20}Ni_{80}$) is the most commonly used material for the ferromagnetic layer, in which the exchange bias is realized, and the antiferromagnet causing this bias is, in many cases, an equiatomic alloy of FeMn [3, 4]. Thus, the $Fe_{20}Ni_{80}$/FeMn film structure refers to the number of common media for magnetic sensors and spintronics. Temperature is an important external factor affecting the hysteresis properties of the ferromagnet/antiferromagnet type multilayers, primarily due to the high thermal sensitivity of the antiferromagnet [5, 6]. To a large extent, this refers to $Fe_{20}Ni_{80}$/FeMn films, since the magnetic ordering temperature of FeMn is relatively small (about 450 K). This research work is devoted to the analysis of the temperature behavior of the exchange bias field in similar and more complex structures with relatively thick layers of permalloy, on the basis of which magnetoresistive sensors can function.

## 2. Experimental procedures

Ta(5)/$Fe_{20}Ni_{80}$(5)/$Fe_{50}Mn_{50}$(20)/$Fe_{20}Ni_{80}$(40)/Ta(5) and Ta(5)/$Fe_{20}Ni_{80}$(5)/$Fe_{50}Mn_{50}$(20)/X(0.2)/ /$Fe_{20}Ni_{80}$(40)/Ta(5) (the layers thicknesses are given in nm) (X = Ta, Gd) multilayered films were prepared by the magnetron sputtering of single-component and alloyed targets onto glass substrates at room temperature (Orion sputtering system, AJA International, Inc). During deposition, the base pressure in the chamber was $5\times10^{-7}$ Torr and the argon sputtering gas pressure was kept $1.6\times10^{-3}$ Torr. The films formation process was accompanied by the applying a high-frequency electric voltage and an external magnetic field (250 Oe) oriented parallel to the substrate plane. The nominal thicknesses and the chemical composition of the layers were adjusted by controlling the rates of sputtering, which are not the same for the used targets.

The deposition of tantalum and permalloy seed layers made it possible to create the conditions necessary for the formation of the fcc lattice in the $Fe_{50}Mn_{50}$ layer. It is known that this crystalline structure is responsible for the formation of the antiferromagnetic ordering in $Fe_{50}Mn_{50}$ films.

The selective X-ray certification of the films under study was carried out on a D8-Advance diffractometer using Co-Kα-radiation. Figure 1 shows the diffraction pattern for Ta/$Fe_{20}Ni_{80}$/FeMn/$Fe_{20}Ni_{80}$/Ta sample, which can be interpreted as follows. In the composition of the film structure, only permalloy with its fcc crystal lattice and the γ-modification of FeMn also possessing fcc crystal lattice are identified. Moreover, in both cases, there is a strong crystalline texture of the (111)-type. Ta reflexes are absent, apparently, due to the small amount of the material. The observed diffraction lines are rather broad, which indicates a highly dispersed microstructure of the sample. The Scherrer formula gives the average crystallite size of about 40 and 20 nm for permalloy and FeMn, respectively.

In order to study the magnetic properties of the considered multilayered film structures, the hysteresis loops $m$(H) in the temperature range of 5÷350 K were measured using the MPMS XL-7. The samples were cooled at the absence of an external magnetic field (ZFC).

## 3. Results and discussion

The magnetic moment $m$ (in emu units) of the samples was measured at the magnetic fields applied in the film plane parallel to the direction of the magnetic field presented during film deposition process. Figure 2 shows the example of the major hysteresis loop $m(H)$ for the Ta/$Fe_{20}Ni_{80}$/FeMn/$Fe_{20}Ni_{80}$/Ta sample measured at room temperature. It consists of two minor hysteresis loops corresponding to the magnetization reversal of two ferromagnetic layers with different thicknesses. As can be seen, the particular loops of both layers are shifted along the magnetic field axis, and the bias magnitudes are different. The thinner layer has a larger bias value due to a smaller magnetic moment. Its properties are not considered in the work, and all attention is focused on the analysis of the properties of the 40 nm thick permalloy layer, the exchange bias field $H_e$ of which at room temperature is about 40 Oe.

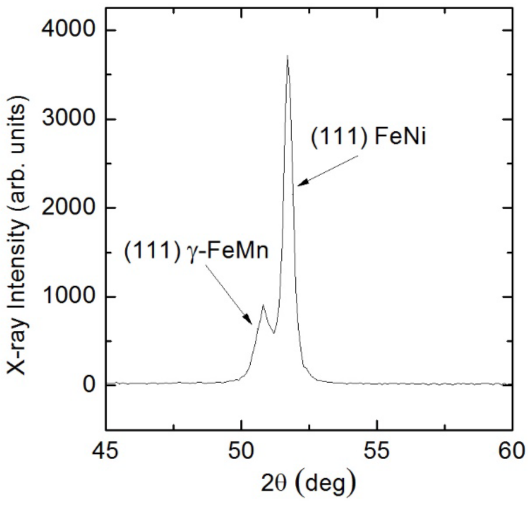


**Figure 1.** X-ray diffraction pattern of the film without spacer Ta/$Fe_{20}Ni_{80}$/$Fe_{50}Mn_{50}$/$Fe_{20}Ni_{80}$/Ta.

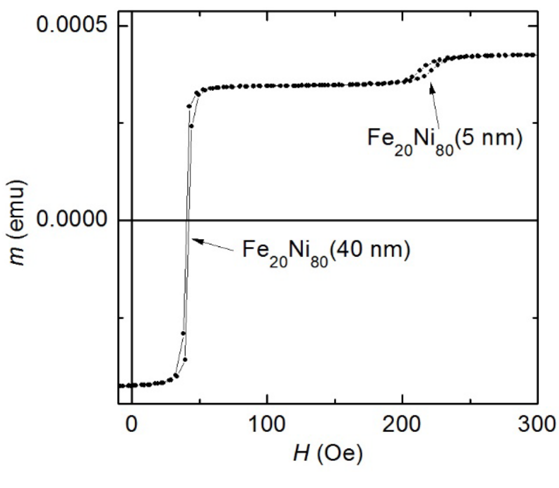


**Figure 2.** Major hysteresis loop for the Ta/$Fe_{20}Ni_{80}$/FeMn/$Fe_{20}Ni_{80}$/Ta sample measured at room temperature.

Figure 3 demonstrates the hysteresis loops of the permalloy layer with a thickness of 40 nm in the Ta/$Fe_{20}Ni_{80}$/FeMn/$Fe_{20}Ni_{80}$/Ta (without a spacer) film structure measured at the temperatures of 5 and

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300 K. The images correspond to the measurements from negative magnetic fields with a positive shift of the hysteresis loops. The value of $H_{c1}$ corresponds to the coercivity of the first magnetization reversal (the forward branch) of the layer, $H_{c2}$ is the coercivity of the second magnetization reversal (the recoil branch) of the layer. The magnitude of the exchange bias field $H_e$, which characterizes the interlayer interaction, is shown schematically in figure 3(a) and can be determined with the well-known formula: $H_e = (H_{c1} + H_{c2})/2$.

It should be noted that throughout the temperature range under consideration, the hysteresis loops have a shape asymmetry, which, as a rule, is typical for the FeNi/FeMn film systems [7, 8]. Basically, this asymmetry is explained by the mechanism proposed in the Mauri model for the exchange bias and consisting in the formation of an exchange spring (parallel domain wall) in the antiferromagnetic layer [9]. In this case, magnetization reversal is understood in terms of the pinning a domain wall in an antiferromagnet [7, 10].

In general, a decrease in the temperature from 350 to 5 K is accompanied by an unambiguous expansion of the hysteresis loop (the increase in the coercivity) of the permalloy layer under study. This may be due to the growth of the $Fe_{20}Ni_{80}$ magnetic anisotropy as well as being a consequence of the increase in the inhomogeneity of the interlayer magnetic interface caused by the dispersion of the anisotropy in the FeMn layer.

The value of the exchange bias field exhibits another behavior (figure 4) consisting in a non-monotonic temperature dependence, which is most often observed in single-crystalline bilayers [6, 11]. When the temperature decreases from 350 K, $H_e$ increases, reaching a maximum in the region of about 150 K, further cooling leads to the reduction of $H_e$ continuing up to 5 K. The first tendency may be associated with an increase in the magnetic anisotropy of the antiferromagnetic layer and with the involvement of small FeMn crystallites with a low blocking temperature in exchange pinning.

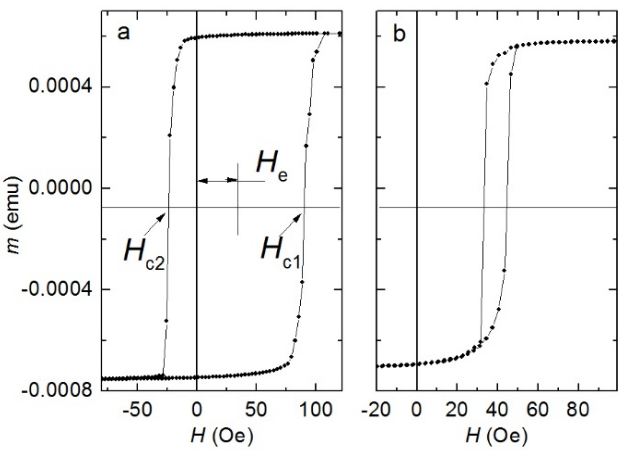


**Figure 3.** Hysteresis loops for the 40 nm thick permalloy layer in the $Ta/Fe_{20}Ni_{80}/FeMn/Fe_{20}Ni_{80}/Ta$ sample measured at 5 K (a) and 300 K (b).

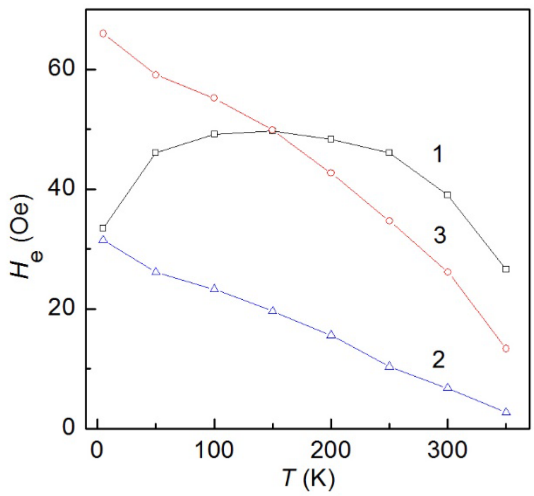


**Figure 4.** Temperature dependences of the exchange bias field in the 40 nm $Fe_{20}Ni_{80}$ ferromagnetic layer separated from the FeMn layer by 0.2 nm thick spacers of various materials: 1 – without a spacer; 2 – Ta; 3 – Gd.

The temperature behavior of $H_e$ was detailed by analyzing $H_{c1}$(T), $H_{c2}$(T) (the curves 1 in figures 5 and 6). It is seen that lowering the temperature leads to a monotonic increase in $H_{c1}$. Obviously, this is a consequence of the increase in the efficiency of the interlayer coupling, since in the permalloy single-layered films, the level of coercivity even at helium temperatures is much less. The reason for this, in turn, is the increase in the FeMn magnetic anisotropy. But the interlayer interaction is

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responsible for both hysteresis and exchange bias. In $H_{c1}$(T) both are reflected. The analysis of $H_{c2}(T)$ may contribute to the separation of these contributions. This dependence is non-monotonous. With a decrease in temperature at the initial stage (up to about 200 K), the rise of $H_{c2}$ reflects a predominant increase in the bias effect. A significant decrease in $H_{c2}$ at low temperatures indicates a strong growth of the magnetic hysteresis. Thus, the non-monotonicity of $H_e(T)$ is indirectly a consequence of the change in the relative role of the exchange bias and the magnetic hysteresis. No less interesting is the fact that at low temperatures $H_{c2}$(T) changes with greater velocity than $H_{c1}(T)$. Probably, the different temperature behavior of the two branches of the hysteresis loop is a reflection of a certain asymmetry in the processes of magnetization reversal, which is typical for such film structures.

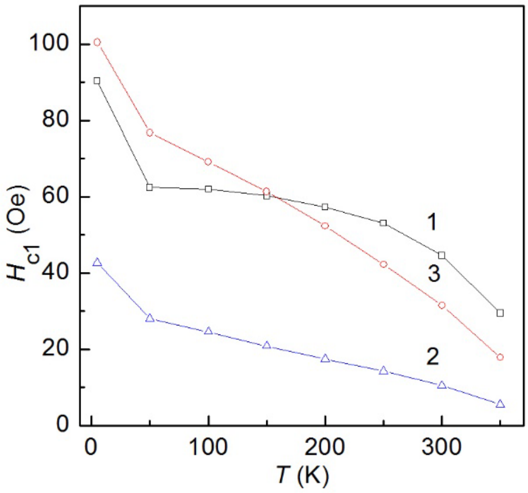


**Figure 5.** Temperature dependences of the coercivity $H_{c1}$ of the 40 nm $Fe_{20}Ni_{80}$ ferromagnetic layer separated from the FeMn layer by 0.2 nm thick spacers of various materials: 1 – without a spacer; 2 – Ta; 3 – Gd.

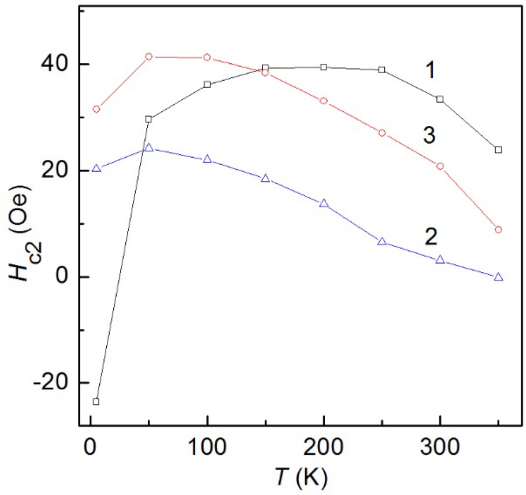


**Figure 6.** Temperature dependences of the coercivity $H_{c2}$ of the 40 nm $Fe_{20}Ni_{80}$ ferromagnetic layer separated from the FeMn layer by 0.2 nm thick spacers of various materials: 1 – without a spacer; 2 – Ta; 3 – Gd.

The interlayer exchange coupling can be modified by introducing nonmagnetic (or weakly magnetic) spacers [12]. Gadolinium, which has ferromagnetic ordering in the temperature range below room temperature, and tantalum, which is a paramagnet in the entire temperature range under consideration, were chosen as such spacers. Gd, however, can also be magnetically ordered at room temperature due to its interaction with permalloy.

Figure 4 shows the temperature dependences $H_e(T)$ for the $Fe_{20}Ni_{80}$ (40 nm) layers in the Ta/$Fe_{20}Ni_{80}$/FeMn/Ta/$Fe_{20}Ni_{80}$/Ta (curve 2) and Ta/$Fe_{20}Ni_{80}$/FeMn/Gd/$Fe_{20}Ni_{80}$/Ta (curve 3) samples. It can be seen that in both cases, the $H_e$ value in the entire temperature range under consideration behaves unambiguously, namely, it increases with decreasing temperature. Thus, the decrease in $H_e(T)$ observed in the film structure without a spacer at the temperatures below 150 K is eliminated. Moreover, the level of the exchange bias for the film with a Gd spacer in the indicated temperature range is much higher than $H_e$ for the film system without a spacer. The use of the paramagnetic layer of tantalum, as expected, reduces the value of the interlayer exchange coupling.

The dependences $H_{c1}(T)$, $H_{c2}(T)$ (figures 5 and 6) for the films with and without spacers are qualitatively similar. However, in quantitative terms, there is a noticeable difference primarily for $H_{c2}(T)$. This can be explained by the weakening of the relative role of the hysteresis effects in the films with spacers introduced between interacting antiferromagnetic and ferromagnetic layers.

## 4. Conclusions

It is shown that the temperature dependence of the exchange bias field in the permalloy layers, which are exchange-coupled with the antiferromagnetic layer of FeMn, is non-monotonous. This is due to the rapid increase in the magnetic hysteresis, which is ahead of the bias effect at low temperatures. The introduction of the ultrathin spacers makes it possible to modify not only the value of the interlayer coupling, but also the nature of its temperature dependence. At the same time, the quantitative side of such modification depends on the spacer material. In particular, the introduction of the paramagnetic spacer of tantalum generally reduces the efficiency of the interlayer exchange coupling, and the gadolinium spacer at low temperatures provides the effect of increasing the exchange bias field compared to the case of the multilayer without a spacer.

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